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1.7 GHz Schottky Monitor System

Ralph J. Pasquinelli
Fermilab

Introduction

A new Schottky monitor system was designed and built for both the Tevatron and Recycler accelerators. The pickups for both machines are identical with one each horizontal and vertical detector installed in each machine. The pickups are also bidirectional allowing the measurement of proton and antiproton (pbar) signals. In the Tevatron, this is a key feature as both species of beam are present simultaneously during a collision store for High Energy Physics (HEP). The system is designed to measure tune, chromaticity, emittance, and momentum spread. Signal processing for the Recycler was straightforward due to the lack of large coherent beam signals. The Tevatron required a different technique, which is the focus of the remainder of this paper.

The system for the Tevatron required significantly different signal conditioning as large coherent longitudinal beam signals are present. Coherent longitudinal signals have been observed in high-energy synchrotrons over the last decade. During the attempts to create a bunched beam stochastic cooling system for the SPS at CERN and the Tevatron at Fermilab, it was observed that harmonics of the longitudinal revolution Schottky spectra were much larger than expected. (Similar results are also reported in HERA at DESY and RHIC at BNL.) The Fourier transform of the time domain signal would indicate that such coherent behavior would not be observed. While several theories from microwave instability to plasma physics exist, an accurate explanation for the phenomena is not yet widely accepted.

System Hardware Description

Pickup Arrays

The pickup is based on the stochastic cooling pickups that were designed for the Debuncher Cooling and Accumulator Core Cooling upgrades.[1, 2] The dimensions were chosen at 109 mm x 75 mm to be larger than any beam pipe aperture in either the Recycler and Tevatron. The desired frequency of operation was to be between 1.5 and 2 GHz because of the availability of existing microwave components. (An effort to keep costs down.) The secondary collection waveguides are standard WR-430 waveguide dimensions so that catalog components could be used in the design. The pickup consists of three sandwiched waveguides, with the center waveguide acting as the beam pipe. The outer waveguides are connected to the central waveguide and coupled by slots whose width and spacing is proportional to the 1.7 GHz center frequency. The number of slots and array length dictate the bandwidth, for this application, 100 MHz. Each end of the array has microwave absorber material on the central waveguide walls (beam pipe) to keep all modes from propagating into or out of the array. The absorber is manufactured by Transtech, provides a minimum of 20 dB isolation, and is ultra high vacuum compatible. (See figure 1) In an effort to save on costs, the vacuum vessels were recycled from the recent Accumulator Core upgrade. These vacuum vessels are 1.4 meters flange to flange and could easily accommodate the length of the array. Ultra high vacuum techniques are utilized throughout the manufacturing process. The arrays were pre-baked at 125 degrees Celsius and were vacuum certified before installation. The tanks are re-baked once installed in the accelerator. For more details, refer to the listed references.

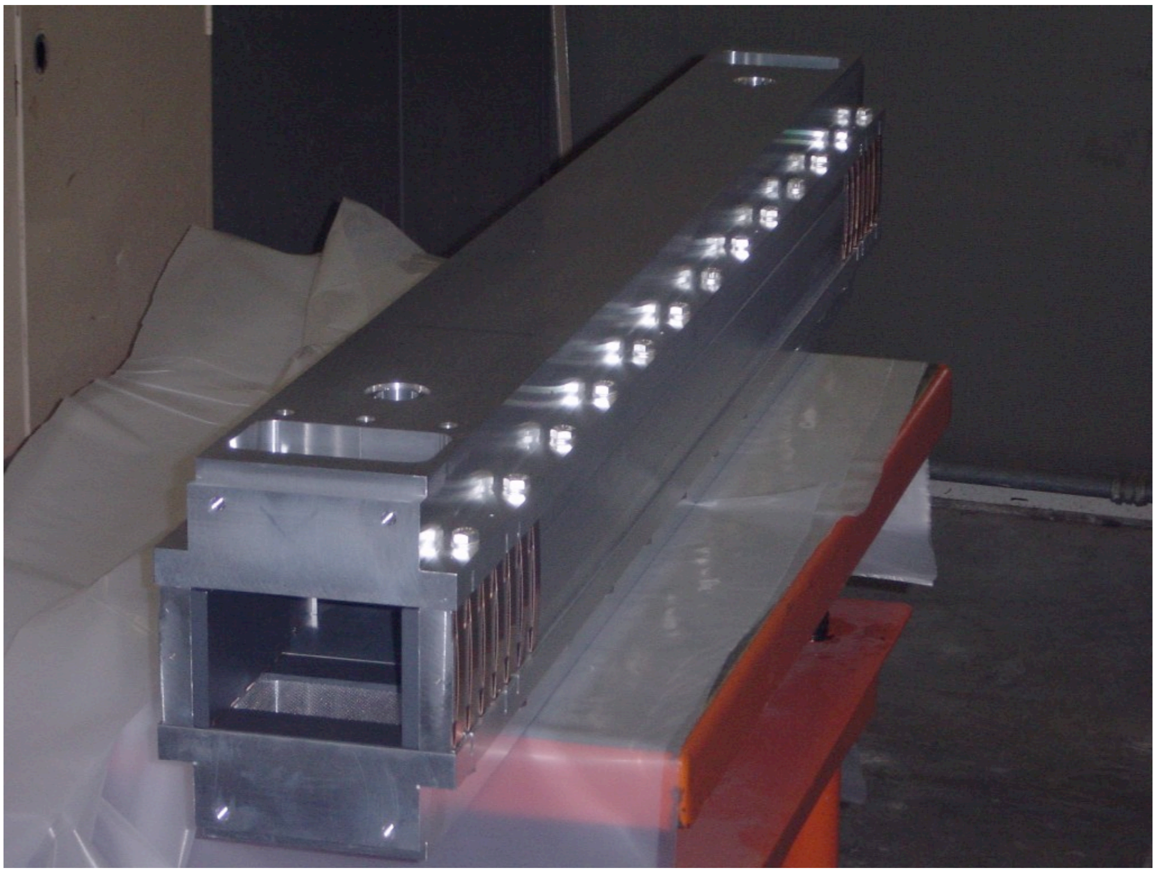

Figure 1. Schottky pickup before insertion into vacuum vessel. Metallic clips on end hold absorbers in position. Waveguide launchers are not installed in this photo.

<u>Signal Processing</u>

Figure 2 is a typical Schottky spectrum from the installed 1.7 GHz Schottky system in the Tevatron. Some initial studies were performed to reduce this longitudinal signal, including signal subtraction and beam centering. In the Recycler, any common mode signal is easily removed by centering the beam in the pickup. For Tevatron stores, the protons and pbars are on helical orbits. This is a means of reducing the beam-beam interactions by preventing unwanted crossings. The helical orbits separate the proton and pbar beams by some six millimeters at the location of the Tevatron Schottky's. Hence, no amount of beam centering will make both beams travel on the central axis of the pickup.

As is evident, the coherent longitudinal component of the transverse signal is five to six orders of magnitude larger than the desired transverse sidebands. This presents a significant challenge to the signal processing. The block diagram for the signal processing is attached at the end of this document. Some preamplification is necessary before the signal is transmitted to the above ground service building. The system also allows for the injection of a test signal before this amplifier, which is utilized for gain calibration. Figure 3 shows the transverse pickup response for the pickup installed in the Recycler ring where coherent effects are not observed. The choice of 100 MHz bandwidth for the pickup is based on the need to have sufficient bandwidth to allow clean gating of the beam signals in the Tevatron, which have a 396-nanosecond spacing of the same species, i.e. proton or antiproton. The location of the pickup in the Tevatron tunnel was chosen so that the crossing between the protons and pbars are 100 nanoseconds apart. While the pickup itself acts as a band pass filter, it does not have sufficiently steep skirts to reject out of band signals. Secondary lobes of signals exist and are well within the pass band of the preamplifier. An additional 100 MHz cavity band pass filter (BPF) needed to be installed before the preamp to avoid saturation. The preamp has a gain of 35 dB and a noise figure of 1.2 dB. Pickup directivity of 12 dB was measured with beam in the Recycler. The ratio of proton to pbar intensities in the Tevatron is about a factor of ten with present operations, i.e. making proton signals on the pbar end of the pickup about as large as the pbar signal. This requires a fast gate to isolate the desired species of beam.

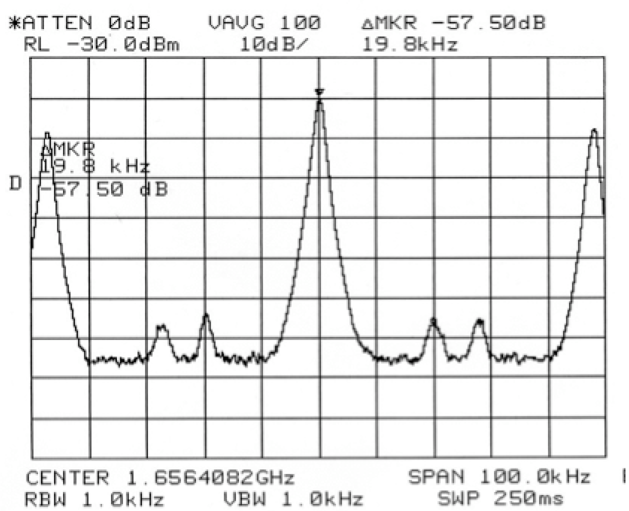

Figure 2: Typical Tevatron Schottky spectrum at 980 GeV showing transverse and coherent longitudinal signals, 36x36 store, total beam current $7x10^{12}$.

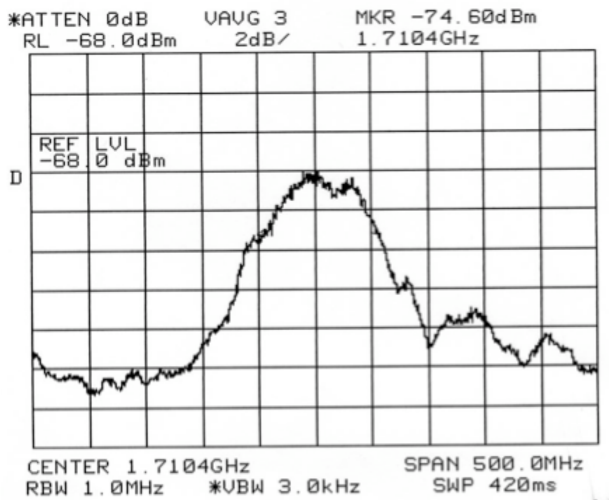

Figure 3: Measured transverse pickup sensitivity. Measurement made in the Recycler with centered beam and zero longitudinal signal. Beam current is 1.4 x 10^{11} protons. Recycler revolution frequency is 89 KHz.

The system utilizes double balanced mixers for the gating function. Fast GaAs switches and PIN diode switches were tried, but the video feed through of the gate drive signal was unacceptable. The gate drive is synchronous to the revolution harmonics, hence conflicts with the output spectrum. To achieve the best on to off switching isolation, a modified TTL driver circuit was built to achieve true zero volts in the zero state. The system cabling between tunnel and upstairs electronics was adjusted so that both pickup difference and sum signal propagation delays to the service building differ by less than 500 pico seconds. This allows use of the sum signal as the beam witness marker when adjusting the gate timing on the local oscilloscope comfort display. The gates are generated from a dedicated gate generator that has the timing information of the bunch spacing in the accelerator. The proton and antiproton revolution markers are utilized to synchronize the timing. There is one gate generator for each of the H and V proton and pbar signals, a total of four. The gates generated are two RF buckets in length, or approximately 38 nanoseconds. Two bucket length was necessary due to the pulse stretching effect of the limited 100 MHz band pass filter on the front end. The gate generators are remotely programmable to allow gating of any combination of bunches. This has shown to be effective in measuring different tunes and chromaticities of leading, middle, or trailing bunches in the 12 bunch trains.

The gating also reduces the system noise by the ratio of N/(0.5*1113), the number of filled to total buckets in the ring divided by two (because of he double bucket gate length). The next critical stage in the processing is to further reduce the signal bandwidth. Having completed the gating, the need for 100 MHz bandwidth vanishes. The transverse information in the signal is the same for all revolution harmonics. A 5 MHz cavity band pass filter is next in the line of signal processing. The reduced bandwidth now allows for additional gain (without saturation) before down conversion to base band.

The Schottky system is also designed to provide chromaticity information. Measuring the difference in frequency width of the upper and lower sidebands derives the chromaticity for the beam. To preserve this information, the down conversion to base band must be done with single sideband techniques to avoid band overlap that occurs from "image" Schottky bands. With the appropriate 90-degree hybrids, mixers, and splitters, a single sideband down converter is the next step in processing. The unwanted image Schottky band is suppressed by more than 20 dB. A phase locked multiplier generates the local oscillator for this down conversion. The input is the 53 MHz LLRF signal. The output is thirty-two times the input frequency, 1.69935 GHz. Utilizing the RF as the input source allows for synchronous down conversion of the signal up the Tevatron ramp. The Tevatron RF changes by 1 KHz (53.103 to 53.104 MHz) from 150-980 GeV.

The down converted signals are made available to the Oscilloscope and Vector Signal Analyzer (VSA) via a 16 x 16 analog multiplexer that is built around the Analog device part number AD8116. Bandwidth of the mux exceeds 100 MHz with a worst-case cross talk of –31 dB at 175 MHz. (Typical cross talk <-40 dB below 100 MHz.) The multiplexer, VSA, oscilloscope, and trigger generators are all remotely controlled via Ethernet connections to the Fermilab ACNET control system.

The VSA is the workhorse for data acquisition. Precise measurement of sideband frequency, widths, and power spectral density yield the required tune, chromaticity, emittance, and momentum spread information. An ACNET software application provides a simple human interface that controls the gating, mux, oscilloscope, VSA, and data analysis. The user makes a selection from the measurement and options menus, which include the selection of protons or pbars or both, bunch selection, or re-measurement. Key parameters of the VSA are available for adjustment as are indication of the input range of the signal. Data can also be emailed to the user for additional analysis. Both the VSA and Oscilloscope screens are broadcasted on the internal TV network for comfort displays. Figure 4 shows a typical out put of the software for the measurement of simultaneous pbar and proton mode.

The system gating allows full flexibility of measurement, but is a single user function. It was decided to add a separate gate circuit and down converter for continually monitoring beam emittance. The gating is set to all 36 bunches of the selected H or V, proton or antiproton signal with a separate gate generator. The down conversion is double sideband as the integral of the power spectral density is the desired parameter and identical for upper and lower sidebands i.e. no need for preserving widths of side bands and saving on parts count in the electronics. The down converted signals are on the order of –105 dBm, requiring significant gain before further processing. The VSA could easily make this measurement, but to have a dedicated emittance calculation, a dedicated VSA would be required. Instead, the down converted signal is passed through a two tap digital FIR notch filter to significantly reduce the longitudinal revolution harmonics.

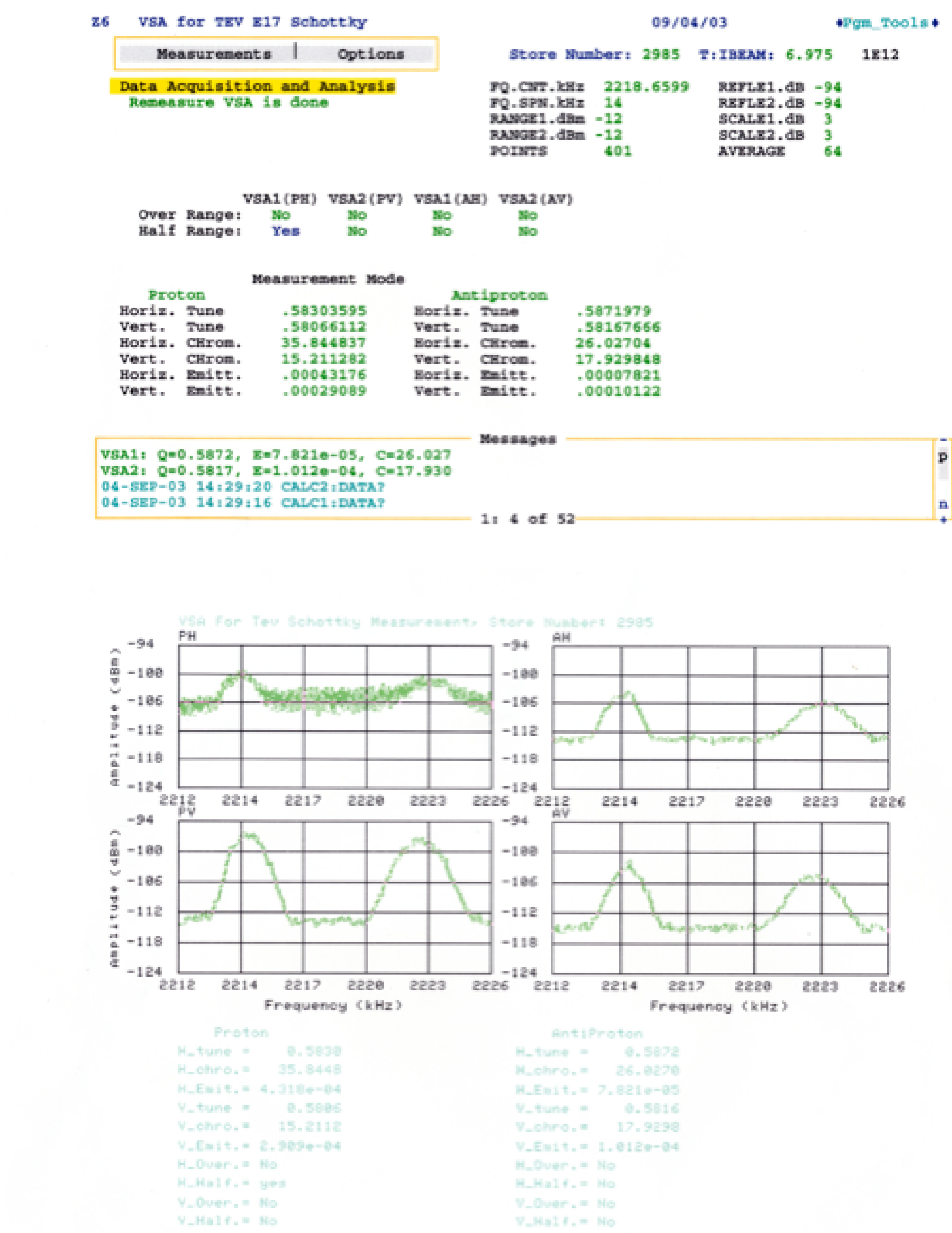

Figure 4. ACNET application page. Top page allows selection of measurement parameters, bottom is graphical output. For this case, all four transverse emittance, tune, and chromaticity measurements are displayed (two each proton and pbars).

This signal is then down converted one last time to base band (DC). The revolution frequency of the Tevatron is 47.717 KHz. The notch filter reduces this line significantly. An active two-pole Butterworth band pass filter centered on 20 KHz does the integration function to provide the area under the lower sideband. This filter also improves the rejection of the 47 KHz revolution component. The output of the BPF is next applied to an Analog Device RMS to DC converter. This voltage is data logged by the control system and is representative of the beam emittance when normalized to the beam current. The emittance voltage is calibrated against a transverse scrapper located at a known beta function in the Tevatron.

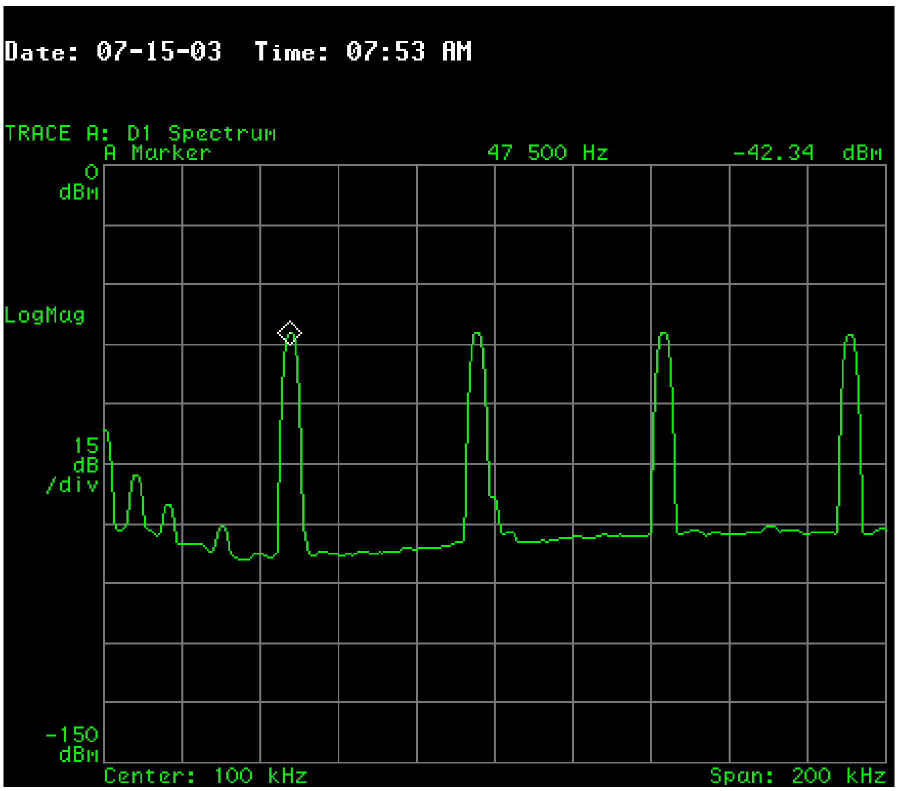

Figure 5. Down converted calibration spectrum with gating selected for one bunch. Harmonics of the 47 KHz revolution frequency are measured as a calibration for system gain.

Due to the large system gain of this Schottky system, it is important to know gain stability if the emittance information is to be trusted. A calibration system was installed which utilizes the same microwave local oscillator that is used for the first down conversion. The signal can be remotely switched on and is transported to the tunnel on a coaxial cable and injected via a directional coupler before the BPF and first amplifier. This tests all of the system electronics with the exception of the first passive hybrid. The calibration must be performed with no beam in the machine, as the beam signal will interfere. Depending on the gating setup chosen, the signal fed to the VSA will contain the gating modulation down converted to base band. The VSA is able to measure this base band modulation to better than 0.1 dB (< 2%) accuracy of the channel gain, figure 5 is an example with single bunch gating selected.

System Performance

The Tevatron and Recycler systems have been installed and are providing non-invasive measurements of tune, chromaticity, momentum spread, and emittance.

Longitudinal Schottky signals in the frequency domain are expressed by

$$\frac{\Delta f}{f_0} = n\eta \frac{\Delta p}{p_0}$$

where Δf is the frequency spread of the Schottky signal, f_o is the revolution frequency, n is the harmonic of the revolution frequency where the signal is observed, η is the slip factor, and $\Delta p/p_o$ is the momentum spread.

The equation describing the frequency spread of transverse Schottky signals is

$$\frac{\Delta f}{f_0} = \left[(n \pm Q)\eta \pm \xi\right]\frac{\Delta p}{p_0}$$

In this equation, Q is the tune, and ξ is the chromaticity. The plus and minus signs correspond to the upper and lower sidebands which have different frequency widths. With some algebraic manipulation and substituting Δf_1 and Δf_2 for Δf (upper and lower sidebands), solve for the value for chromaticity

$$\xi = -\eta\left[n\left(\frac{\Delta f_1 - \Delta f_2}{\Delta f_1 + \Delta f_2}\right) - Q\right]$$

For the Tevatron, η is equal to 2.83 x 10^{-3}, Q is on the order of 20.580, f_0 is 47,717 Hz, and n at 1.7 GHz is on the order of 35,600. Figure 6 depicts a typical VSA measurement for the proton signal. The plot is zoomed in on the transverse sidebands, longitudinal line is off screen. The difference in frequency width between the upper and lower sideband clearly provides information for chromaticity calculation. The application program does a fit to the data to determine the frequencies and widths. This instrumentation has allowed, for the first time, parasitic measurement of antiproton parameters in the presence of protons during collider operation.

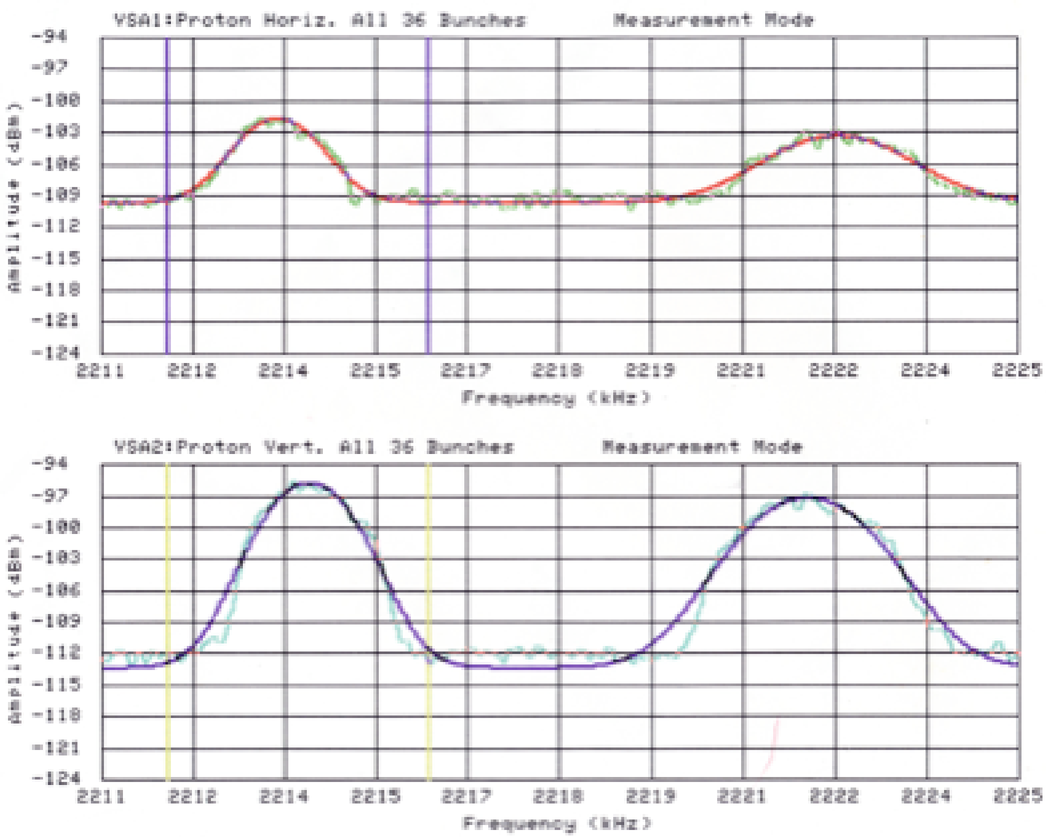

Figure 6. Detailed measurement results of proton transverse Schottky signals including the curve fit that provides the tune frequencies and chromaticity information.

Another mode of operation is that of monitoring signals up the acceleration ramp. The VSA memory buffer length is set to its maximum and gating is done via the ACNET Tevatron Clock system. Five minutes of continuous data is captured on each ramp. Figure 7 is a spectrogram of the Horizontal proton signal. Figure 8 shows the processing electronics housed in two relay racks in the E17 service building, Figure 9 the tanks installed in the Tevatron tunnel.

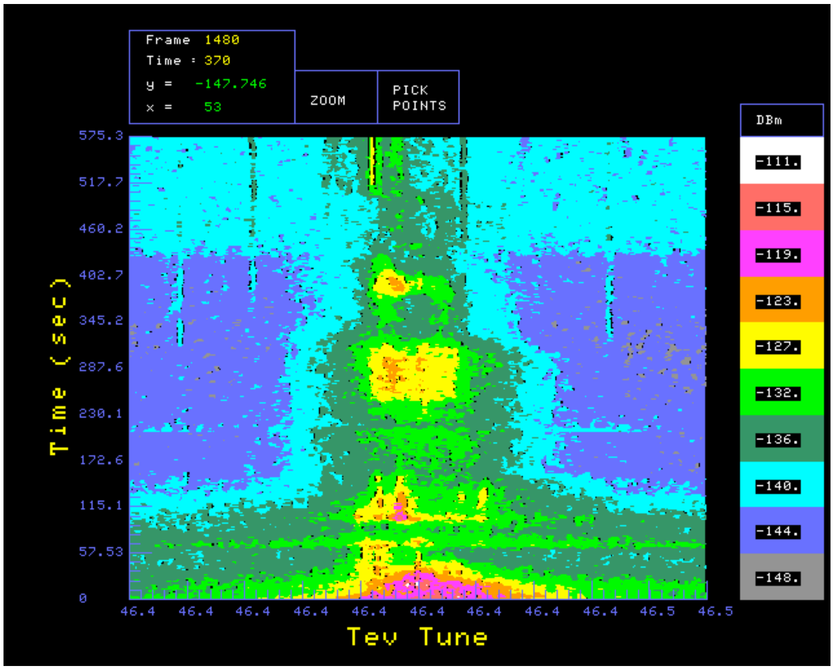

Figure 7. VSA spectrogram measurement of horizontal tune line up the ramp and through the squeeze. Five minutes of data. Notice that amplitude of the signal fluctuates significantly due to coherent beam phenomena.

Figure 8. Tevatron Schottky electronics in E17 service building.

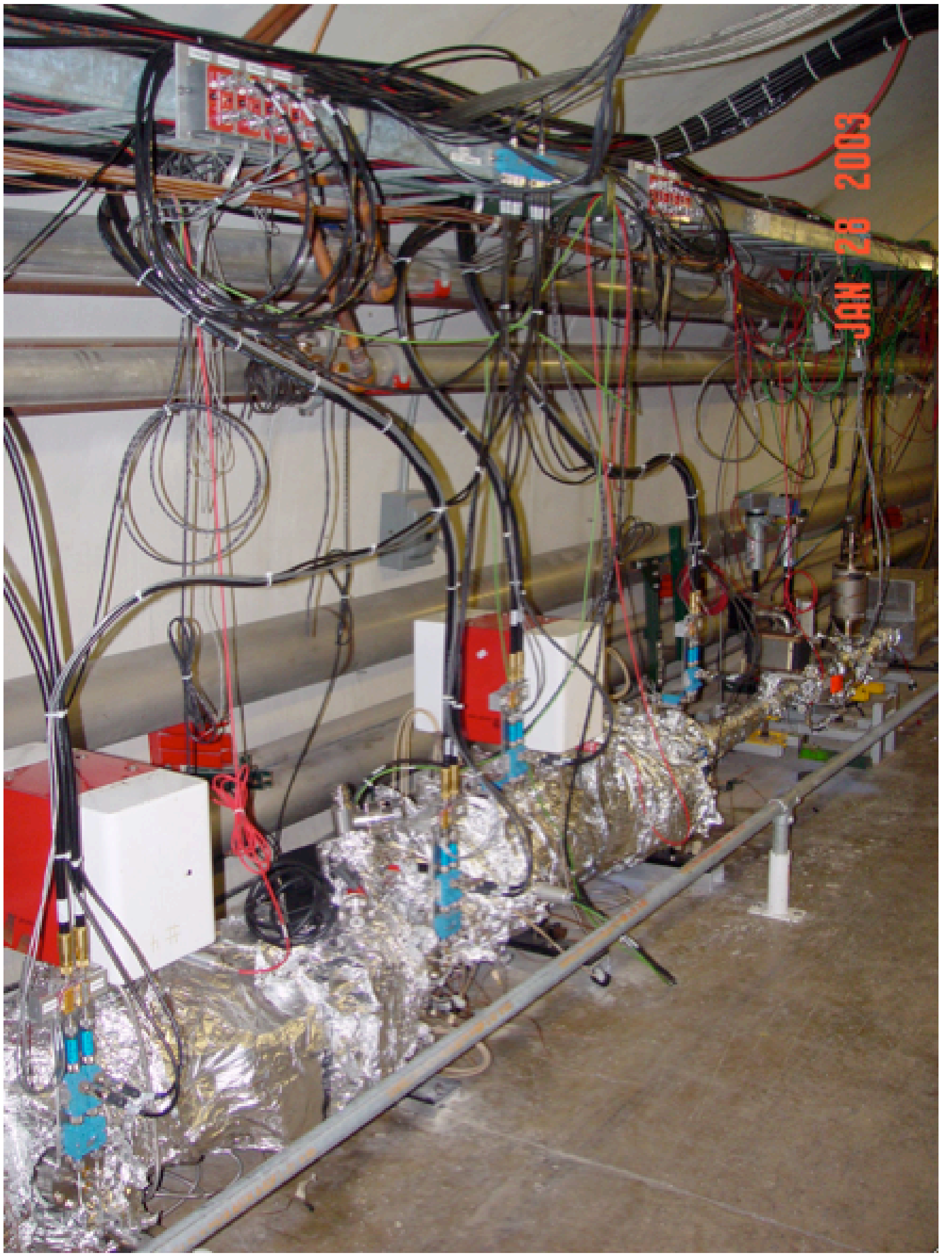

Figure 9. 1.7 GHz Schottky pickups installed in the E17 straight section of the Tevatron. Foil is bake out insulation. Preamps and hybrids attached to tanks, other electronics mounted out of way on cable tray.

References

[1] D. McGinnis, Slotted Waveguide Slow-Wave Stochastic Cooling Arrays, PAC '99, New York

[2] D. McGinnis, The 4-8 GHz Stochastic Cooling Upgrade for the Fermilab Debuncher, PAC '99. New York,